AD-A154 791 PRECISION MICROWAVE ATTENUATION MEASUREMENT BY TIME INTERVAL RATIO(U) ROYAL SIGNALS AND RADAR ESTABLISHMENT MALVERN (ENGLAND) P CUMMINGS ET AL. MAR 85 RSRE-85005 1/1

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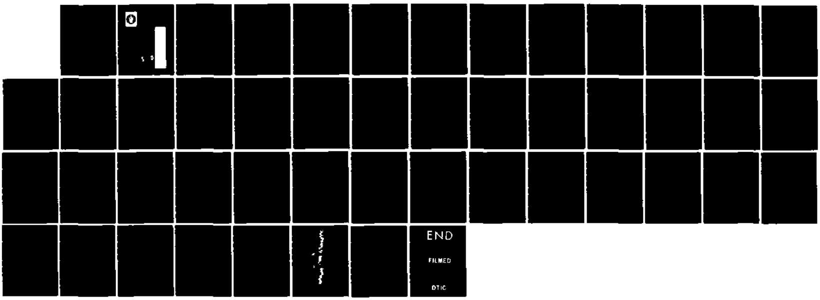

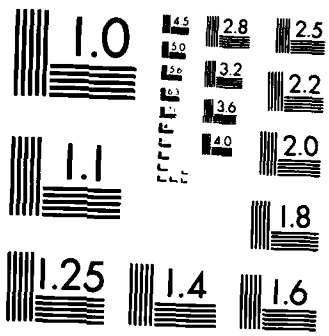

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ROYAL SIGNALS AND RADAR ESTABLISHMENT, MALVERN

PRECISION MICROWAVE ATTENUATION MEASUREMENT BY TIME INTERVAL RATIO

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March 1985

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ABSTRACT

A method of measuring microwave attenuation by substitution described. As attenuation is inserted into the device under test, the pulse repetition frequency of a pulse modulated PIN diode switch in series with the device is changed to maintain a constant mean power output from the circuit. The ratio of the pulse repetition frequencies before and after insertion is shown to be simply related to the attenuation of the device under test.

Sources of error are examined in detail and results are quoted showing inaccuracies of less than $\pm$ 0.002 dB over a range of 0 to 20 dB.

S83/16

Contents

1.0 Introduction

2.0 System Operation

3.0 Theoretical Performance

4.0 Sources of Error

4.1 The microwave power source

4.2 The 20 dB coupler

4.3 The reference arm level setting attenuator

4.4 The PIN diode and driver

4.5 PIN diode losses due to internal harmonic generation

4.6 Power head and amplifier inaccuracies

4.7 Beating at the output of the dc amplifier

4.8 Coaxial components and interconnections

4.9 Leakage

4.10 Digital voltmeter errors

4.11 Mismatch error

4.12 Summary of practical values

4.13 Calculating a value for the error budget

5.0 System Sensitivity and Stability

6.0 Detailed Automated Measurement Technique

7.0 Measurement Results

8.0 Conclusions

9.0 Acknowledgements

10.0 References

11.0 Bibliography

A.1.0 Appendix 1

A.2.0 Appendix 2

A.3.0 Appendix 3

Tables

Figures

1.0 Introduction

Many methods of measuring microwave attenuation are used in the United Kingdom National Standards Laboratory (1), but a revision of techniques is continuously undertaken to try to reduce the cost of the operation, either by the introduction of automated measurement procedures or by the introduction of more cost effective equipment (2).

The Time Ratio Attenuator Calibrator was originally envisaged as a relatively simple low cost and wide band system for the measurement of attenuation up to 30 dB. The performance of the system shown in figure 1 was thoroughly investigated in order to ascertain whether this type of calibrator was suitable for national standards calibrations. The system was operated at a frequency of 10 GHz for convenience and the availability of components.

This calibrator and two other similar systems independently proposed have each been patented (3, 4, 5).

2.0 System operation (refer to figure 1)

The cw source is frequency stabilized and levelled, and is fed into a computer controlled 0-70 dB step attenuator. This series attenuator is switched into the system during a change in the pulse generator parameters - the need for this is discussed later. A fraction of the power is fed via a 20 dB coupler into a reference arm containing the reference attenuator and a 1mW thin film thermoelectric (TFT) power head. The through path of the 20 dB coupler feeds the measurement arm of the system.

The measurement arm consists of the device under test (DUT) sandwiched between matched isolators followed by a variable period, constant pulse width, switched PIN diode attenuator. This is driven by a computer controlled HP 5359A

Time Synthesizer which allows the switching period, T, of the PIN diode to be changed accurately in steps of 1nS. The mean of the switched power, Pm, is then measured using another TFT power head of the same type as used in the reference channel. The high pass filter preceding the measurement channel power head removes the component of the signal which is generated by the PIN diode switching waveform.

The power heads are modified and connected together in such a way as to generate a difference voltage which is fed into a Marconi power meter and thence through external amplification and smoothing to a high quality digital voltmeter.

When performing a calibration the DUT is set to its reference position (say 0.0000 degrees on a precision rotary vane attenuator) and the period of the PIN attenuator drive pulse is adjusted until the mean power Pm is equal to the reference power Pr. The period T' is then noted by the computer as giving a null on the DVM. An attenuation A is then inserted in the DUT and the period of the drive pulse again adjusted to give a null on the DVM. This gives a second period T" which is also noted by the computer. Ideally, as the power Pr has not been altered, the attenuation inserted into the DUT must have been removed from the PIN switch to restore the null condition. Replacing the two power levels by the two periods in the definition of attenuation results in the equation:-

$$A = 10 \times \log (T''/T') \text{ dB}$$

This sequence is repeated six times to achieve a statistically acceptable result.

3.0 Theoretical Performance

Let the measurement parameters be as indicated in Figure 1, where:

A	=	attenuation, dB, through DUT.
A_a	=	difference in attenuation, dB, of DUT between calibration and reference settings.
L	=	fixed attenuation, dB, of other components in the measurement channel.
P_i	=	power entering DUT.
P_o	=	power leaving DUT.
P_r	=	power received by detector in reference channel.
P_m	=	mean power received by detector in measurement channel.
P_n	=	RMS noise equivalent power for one detector referred to detector output.
T	=	switching pulse period.
t	=	switching pulse length.
R_a	=	noise equivalent input resistance of amplifier.
$R_m = R_r$	=	noise equivalent resistance of detectors, assumed equal.
g	=	fraction of incident power transmitted through the PIN diode when passing RF.
h	=	fraction of power emerging from the PIN diode at the fundamental frequency.
A_p	=	attenuation (isolation), dB, of PIN diode in off-state.

Primed and double-primed values, eg P', P'', represent measurements made at the reference and unknown settings of the DUT.

The mean powers reaching the detector in the measurement channel at the two settings of the DUT are given by:

$$P_m' = P_i . 10^{-L/10} . 10^{-A'/10} \left(\frac{g'h't'}{T'} + \frac{(T'-t')}{T'} . 10^{-A_p/10} \right) \quad (1)$$

and $$P_m'' = P_i . 10^{-L/10} \; 10^{-A''/10} \left(\frac{g''h''t''}{T''} + \frac{(T''-t'')}{T''} . 10^{-A_p/10} \right) \quad (2)$$

Hence $$A''-A' = A_a = 10 \log_{10} \left[\frac{P_m'T'}{P_m''T''} \left\{ \frac{t''g''h''+(T''-t''). \; 10^{-A_p/10}}{t'g'h'+(T'-t'). \; 10^{-A_p/10}} \right\} \right] \quad (3)$$

If P_m, g, h, and t are approximately constant the attenuation error due to A_p is given by

$$\delta A_a = 10 \log_{10} \left[\frac{T'}{T''} \left\{ \frac{1+ \frac{T''-t}{ght} . \; 10^{-A_p/10}}{1+ \frac{T'-t}{ght} . \; 10^{-A_p/10}} \right\} \right] - 10 \log_{10} \frac{T'}{T''}$$

from which $$\delta A_a \approx -4.343 \; 10^{-A_p/10} \frac{T'}{t} \; \frac{(1-10^{-A_a/10})}{gh} \quad (4)$$

When A_p is large the attenuation measurement error is

$$\delta A_a = 4.343 \left\{ \frac{\delta P_m'}{P_m'} - \frac{\delta P_m''}{P_m''} + \frac{\delta T'}{T'} - \frac{\delta T''}{T''} + \frac{\delta t''}{t''} - \frac{\delta t'}{t'} + \frac{\delta g''}{g''} - \frac{\delta g'}{g'} + \frac{\delta h''}{h''} - \frac{\delta h'}{h'} \right\} \quad (5)$$

where $P_m' = P_m'' = P_r$ at balance, $\delta P_m'$ and $\delta P_m''$ represent noise fluctuations of the true values of P_m' and P_m'' and $\delta T'$ and $\delta T''$ represent errors in time interval measurement.

It can be shown that the rms equivalent noise input power to an amplifier with two TFT detectors in series, compared with a single detector, is increased by a factor $(R_r + R_m + R_a)/(R_m + R_a)$.

In equation (5) $\delta P_m' = \delta P_m'' = \frac{R_r+R_m+R_a}{R_m+R_a} \cdot P_n$

If the pulse modulation duty cycle is set by varying the period, T, while maintaining the pulse length, t, constant, $t' \approx t''$ and $\frac{\delta t''}{t''} - \frac{\delta t'}{t'} = \frac{\delta t}{t}$

Similarly, $\frac{\delta g''}{g''} - \frac{\delta g'}{g'} = \frac{\delta g}{g}$ represents any fractional change in the mean power transmission through the PIN diode between measurements.

Also $\frac{\delta h''}{h''} - \frac{\delta h'}{h'} = \frac{\delta h}{h}$ represents any fractional change in power in the operating bandwidth between measurements caused by a change in harmonic content.

The maximum error $\delta\hat{A}_a$ is given by

$$\delta\hat{A}_a = 4.343 \left\{ 2 \frac{\hat{\hat{P}}_n}{P_r}\left(\frac{R_r+R_m+R_a}{R_m+R_a}\right) + \frac{\delta\hat{T}'}{T'} + \frac{\delta\hat{T}''}{T''} + \frac{\delta t}{t} + \frac{\delta g}{g} + \frac{\delta h}{h} \right\} \qquad (6)$$

where peak values are indicated by ^.

4.0 Sources of Error

This section describes the expected sources of error and their effects on the final result:

4.1 The microwave power source

The source used in the final system was a standard CV2346 klystron giving approximately 50mW at 10 GHz. The klystron was phase locked using a Microwave Systems type MOS lock box to give a frequency stability of better than ± 1kHz er 30 minutes. The amplitude was stabilized using a precision PIN diode evelling loop that reduced the input power level by 2-3 dB. This gave ore than sufficient amplitude and frequency stability for the system.

riginally a 1 watt IMPATT oscillator was used to supply the circuit but his was found to have inadequate spectral purity; the klystron signal was ess than 10 kHz wide at 30 dB down whereas the IMPATT was never less than 00 kHz wide.

hecks were made on the system to determine the effects of both frequency nd amplitude variations in the source. When a step frequency or a step mplitude change was introduced, a short term (about 20 seconds) imbalance ccurred at the power meter output. However when gradual changes of 4kHz and ± 20% power level were introduced, no effect was observed at the utput. This implies that although the overall system is reasonably frequency nd power independent (at least over small ranges) there is a need to stabi-ise the source to minimise transient thermal effects at the power measuring eads.

.2 The 20 dB coupler

he coaxial 20 dB coupler originally used to feed power into the reference rm was found to be unsuitable as it suffered from a very high temperature oefficient of attenuation. When it was replaced by a high quality waveguide oupler the repeatability of the system was increased by a factor of eight.

.3 The reference arm level setting attenuator

he setting of this attenuator was not altered during the measurement, so ts repeatability was not tested. However, the stability of the attenuator s important as the proportion of power entering the TFT head must remain constant throughout the measurement. No instability problems were encountered when the attenuator was heavily lagged as a precaution against thermally induced variations.

4.4 The PIN diode and driver

The PIN diode used (Microwave Associates type ML 17280-13) was chosen for its fast switching speed (quoted as better than 5nS rise time) and its excellent isolation across the band 2-18 GHz (greater than 80 dB). Three diodes of the same type were used throughout the experiments and they gave nearly identical results. The PIN diode was driven by a simple circuit (figure 2) designed to give fast repeatable leading and falling edges to the pulse with as little complexity as possible. The positive and negative drives necessary for switching the PIN diode hard on and off were achieved by offsetting the earth to the PIN diode and placing a dc block on each side of it. Tests were carried out on the synthesizer-driver-diode combination to try to detect and eliminate errors (see appendix 1). These tests showed that errors due to variations in the supply to the PIN driver and switch and also thermal variations in the diode itself had little effect on the final result so long as certain restrictions were observed. Errors due to variations in the time synthesizer output are included in the error budget.

4.5 PIN diode losses due to internal harmonic generation

No second harmonic could be detected at 20 GHz using an HP 8565A spectrum analyser. It was therefore assumed that any harmonics present were at least 80 dB down on the carrier.

Power head and amplifier inaccuracies

›bject of using a thin film thermoelectric power head was to allow the ıring head to thermally integrate the pulsed power from the PIN diode :h, thus it was necessary to ensure that no errors were incurred due to :ime constant of the head being too short. As the amplifier was of a ›er-type design it had an extremely narrow bandwidth which could reject ›mponents present on the input from the measurement head, and could ›fore cause a systematic error in the measurement. A study of the ifier by injecting an ac component into the input proved that no problems d be encountered as long as the ac component was less than 20 times the num ripple expected.

linearity of the amplifier was checked over the operational range of OmV at the DVM, the result showed that the amplifier gave no significant r due to non-linearity. The power heads may be non-linear but no method esting has been evolved which is accurate enough to carry out a check. problem was minimised by keeping the power levels at the heads as constant ossible.

mal effects in the power heads are a major problem. Two different effects apparent:

a) variations in the output voltages of the heads due to temperature changes in the environment;

b) variations in the output voltages of the heads due to the thermal lag after a change in power incident on the head.

have been detected. Such an experiment has been conducted and the resulting errors are shown in table 5.

It can be seen that errors do exist with pulse widths below 6 μS, these errors are significant in calibrations and are thus to be avoided. In the measurements carried out during the evaluation of the system the errors were minimised by maintaining the pulse width at values greater than 6.5 μS. Note that errors can still occur when the space width falls below 6.5 μS. This has been partially allowed for by incorporating the errors from the time synthesizer into the error budget.

e values finally chosen for the system were a negative supply of -6.37 volts 0.01 volts), and a positive supply of +1.69 volts (± 0.01 volts). A nstant current driver was originally envisaged for the PIN, but this was ought unnecessary after the findings shown in tables 2 and 3.

1.2 The effects of heating in the PIN diode

o types of heating were investigated; dc heating from the PIN diode bias rrent; and microwave heating.

the PIN was significantly affected by changes in dc bias current then it uld have been observed in the results achieved in table 2. This was found t to be the case and the effect has therefore been ignored.

inspect microwave heating effects, two 5 dB steps were measured with a ecision rotary vane attenuator. The two measurements were made over the nges 0.000 degrees to 41.418 degrees (0-5 dB) and 41.418 degrees to 55.782 grees (5-10 dB). Thus the second measurement was made with 5 dB less peak wer falling on the PIN diode switch. The results of the test are shown table 4. No significant error has been introduced by the reduction in wer.

1.3 Errors in the period or pulse width

e absolute accuracies of period and pulse width are not essential, any accuracies will cancel during the ratio calculation of attenuation. Errors ll occur however if the relative values of period are not correct or if the lse width changes during a measurement. These inaccuracies can be detected varying the pulse width and period such that the mark space ratio stays nstant. During such a test, the balance position of the system should stay e same - if it does not then an error in the pulse width or period will

A.1.0 Appendix 1

The following is a brief description of tests carried out on the PIN diode, diode driver and time synthesizer combination.

A.1.1 The effect of supply voltage variations on PIN diode performance

Tables 2 and 3 show the measurement errors resulting from controlled supply voltage changes to either the positive or negative supply rail feeding the PIN diode switch.

Referring to table 2 it can be seen that no significant variations can be detected in the measured attenuation provided that the positive supply voltage lies between +1.1 and +3.29 volts.

Note that this range cannot be exceeded. A voltage greater than 3.3 volts could cause permanent damage to the diode due to excessive forward current. A voltage below 1.08 volts does not provide sufficient bias for the PIN to switch off the microwave power. In this condition it is not possible to achieve a balance.

Table 3 shows that there are no significant variations in the measured attenuation provided that the negative supply voltage lies between -4.02 and -6.4 volts.

Outside this range, however, the PIN performance becomes much more critical than in the positive case, and significant errors in the measured attenuation occur at PIN voltages between -3 and -1.97 volts. Under these conditions, the PIN diode is not being driven hard enough in the reverse direction, causing the insertion loss of the switch to become significant (ie the difference between the on and off state attenuation is now less than [illegible] dB).

10.0 References

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Therefore, as a calibrator for use at national standards level, the time ratio system seems at present to be uneconomical and comparatively restricted when shown alongside current methods. However, we believe measurements of accuracy acceptable for general laboratory use could be achieved quite cheaply and conveniently with a similar system.

9.0 Acknowledgements

The authors would like to express their thanks to colleagues in the RSRE Microwave Standards Division who have helped during the course of this work. In particular Mr Tim Smith carried out a large proportion of the measurements necessary during the period of this report.

the reference channel it was not possible to measure attenuations of above approximately 23 dB as there was insufficient power in the measurement channel to achieve a balance. The dynamic range for the accuracy required is therefore 23 dB. However, by accepting a reduction in accuracy to about 0.01 dB it is possible to achieve measurements at 30 dB by increasing the reference attenuator thus reducing the power required in the measurement arm to balance P_r.

8.0 Conclusions

The envisaged system was a wideband coaxial system with an accuracy equal to existing national standards calibrators, its main advantages being its low capital cost and ratio type measurement. Unfortunately the dynamic range is low, only approximately 23 dB at full accuracy, and this accuracy is only possible with waveguide components which limit the bandwidth severely. A hybrid waveguide and coaxial system seemed to be the answer and was the system finally used to achieve the results shown. However two major problems still remain; beating, and the length of time needed to make a calibration. The beating between the pulsed microwave power and the dc amplifier chopper is a great problem and the only solution would seem to be to obtain a non-chopper dc amplifier with chopper type accuracy, a difficult if not impossible task even with state of the art components. The other major problem is the comparatively long time required to complete a measurement. Whereas a full calibration of a precision rotary vane attenuator may take up to one week on the voltage ratio system, it would take more than four weeks with the time ratio system and the initial capital savings would soon be offset by the increased operating costs. Some reduction of the time required for a calibration would be possible if a continuously variable pulse generator was used such that the disturbance caused by changing the period could be minimised.

achieved by inserting 70 dB into the series attenuator to effectively switch off the microwave power to the reference and measurement heads. A reading of the amplifier output voltage was then made in the usual way after a settling time of approximately fifteen seconds.

All these steps required a significant amount of time at each balance position and, in all, seven nulls had to be achieved to obtain a statistically acceptable result. This led to an overall calibration time for one attenuation setting on a rotary vane attenuator of greater than 12 minutes. For only one measurement this may be acceptable but for a full calibration it may add weeks to the total time. This time could be reduced by introducing a continuously variable pulse generator. In this case, the effects of changing the period would be reduced as the generator output would not be suppressed during a change in its parameters. This would minimise the disturbance to the system when a small change is required.

A flow chart showing the major steps necessary for calibrating a rotary vane attenuator is reproduced in appendix 2.

7.0 Measurement Results

Table 1 compares two sets of results achieved on the time ratio calibrator with those obtained by calibrating the same devices (between the same matching units) on the national standard voltage ratio attenuator calibrator (2). The first set is for a precision rotary vane attenuator and the second is for a precision dual switched coupler travelling standard.

Both sets of results agree to within the error limits set for the two systems. However the time taken to achieve those results on the time ratio system was approximately three times that for the voltage ratio system. With 10 dB in hour from switch on, assuming that all reference crystals in the system were previously at operating temperature, the long term drift of the system was less than ± 0.001 dB per hour. The short term drift was less than ± 0.0008 dB per minute. The drifts and the effect of introducing a 0.001 dB step into the DUT can be seen in Figure 3.

6.0 Detailed Automated Measurement Technique

The system was operated by a Hewlett Packard HP 85 desktop computer via an IEEE 488 interface bus as shown in fig 1. The program, written in BASIC, is listed in appendix 3 (note that this program is specific to the calibration of a precision rotary vane attenuator, other devices require differing programs).

To obtain each value of the balance period, T, the output from the power meter must be nulled. As the output from the amplifier was extremely noisy, the mean of ten digital voltmeter readings was taken at each measurement point during a three point step and measure technique, the period being changed at each step by a small increment. A least squares fitting program was then used on the three points to achieve a fit to a straight line of period against output voltage. From this straight line equation, the period necessary for zero output voltage was obtained. Experience with the calibrator showed that with an initial error of approximately 1% in the period, a balance could be achieved in two passes. During a measurement, only the first balance at each new attenuation value had to be balanced with more than one pass.

Unfortunately, due to the short term instability of the system it was found necessary to correct each individual period measurement for drift. This was

4.13 Calculating a value for the error budget

With a levelled input power of $P_i \approx 16$mW, the reference head power was $P_r = 10\mu$W. If the pulse length is fixed so that $t = 20\ \mu$S, then at the reference setting of the DUT, $T' \approx 4$mS and with $A_a = 20$ dB added attenuation in the DUT, $T'' \approx 40\ \mu$S. Substituting these figures in equation (6), with $\delta\hat{T} < 1$nS, $R_m = R_r = 200$ ohm and $R_a = 1500$ ohm, gives

$$\delta\hat{A}_a = 4.34 \left\{ 2.\ \frac{\hat{P}_n}{P_r}\left(\frac{R_r+R_m+R_a}{R_m+R_a}\right) + \frac{\delta\hat{T}'}{T'} + \frac{\delta\hat{T}''}{T''} + \frac{\delta t}{t} + \frac{\delta g}{g} + \frac{\delta h}{h} \right\} \qquad (6)$$

$$= 4.34 \left\{ 2.\ \frac{10^{-9}}{10^{-5}}\left(\frac{200+200+1500}{200+1500}\right) + \frac{10^{-9}}{4\text{x}10^{-3}} + \frac{10^{-9}}{4\text{x}10^{-5}} + 0 + 0 + 0 \right\}$$

$$\approx \pm\ 1.1 \times 10^{-3}\ \text{dB}$$

The first term represents random noise and is the most significant. Thus, the worst combination of errors produces a maximum measurement error of $\pm$ 0.0011 dB when $A_a = 20$ dB. Also, substituting $A_p = 80$ dB and $gh \approx 1$ in equation (4) shows that leakage through the PIN switch in the off position contributes an attenuation measurement error not exceeding -0.00001 dB for $A_a = 20$ dB and proportionately more for larger values of A_a.

5.0 System Sensitivity and Stability

The sources of error described in the previous section gave rise to long and short term drifts in the system output. To ascertain the magnitude of these drifts, the power meter output was fed into a chart recorder and monitored for several days. After a settling period of approximately one limitations the effective RF pulse length may differ from that of the pulse generator. The pulse length, t, which should be independent of duty cycle, was not changed during an individual calibration, and no variation, δt, was conclusively detected at different duty cycles.

Attenuation through the PIN diode when passing RF at 10 GHz was measured to be about 1.0 dB. Variation with temperature was about 0.001 dB/^{o}C, and with drive voltage about 0.1 dB/Volt. Any variation of PIN diode drive voltage with duty cycle would introduce a systematic error which would be represented in the value of g. No such variation was observed.

The attenuation (isolation), A_p, of the PIN diode switch was > 80 dB, and with 10mW power at 10 GHz incident on the PIN diode no second harmonic could be detected with a spectrum analyser sensitivity of -80 dBm, showing the harmonic power generated to be negligible.

The thin film thermocouple detectors (Marconi 6422) have a maximum power rating of 1mW and a thermal time constant of about 10mS. Since the peak-to-peak alternating component of the measuring thermocouple output voltage is about 40% of the dc level for a thermal time constant of 10mS and a pulse period of 4mS and the difference between the measuring and reference thermocouple output voltages is amplified by a high gain dc amplifier, it is important that there should be sufficient filtering in the early stages of the amplifier to prevent overload or non-linearity effects. Measurements confirmed that non-linearity effects could only be detected if the alternating component of the amplifier input voltage was increased to over 20 times the actual maximum value.

4.11 Mismatch error

Mismatch error is the largest single source of error in the system. It has been minimised by placing a tuner and isolator combination on each side of the device under test. Further information on mismatch can be obtained from reference 1.

Note that mismatch error is not included in this error evaluation as the absolute value is dependent on the care taken adjusting the matching unit tuners. A typical maximum mismatch error under these conditions would be approximately ± 0.002 dB per 20 dB in the rotary vane attenuator.

Comparisons shown in table 1 do not include relative mismatch errors as the matching units were transferred intact with the rotary vane attenuator, thus effectively eliminating mismatch uncertainty from the comparison.

4.12 Summary of Practical Values

The peak noise power, $\hat{P}_n$, specified for the standard dc chopper amplifier (Marconi-Sanders 6460) is about 6nW at maximum sensitivity. Addition of further amplification with increased smoothing reduced the peak noise to about 1nW.

The pulse generator (Hewlett-Packard 5359A) has a specified accuracy of ± 1ns with resolution < 1nS, with the contribution from the specified time base error of ± 2nS/sec rms for pulse periods of $> 10^{-2}$ sec being negligible. The output from this pulse generator was amplified by a VMOSFET switching transistor to provide + 10mA and -10V as required by the PIN diode switch. Direct coupling to the PIN diode was achieved by isolating the latter from the adjacent coaxial lines by dc blocks. Because of amplifier and PIN switch

4.8 Coaxial components and interconnections

It has already been stated that a factor of 8 increase in repeatability was achieved by replacing a 20 dB coaxial coupler with a waveguide coupler. This was due to the thermal stability of the coupler being too poor (an approximate change of 0.003 dB per degree Celsius) for the purpose for which it was being used. This also applied to semirigid coaxial cables which had to be well lagged with cotton wool and kept as short as possible to achieve maximum stability. In fact all the coaxial components had to be thermally insulated to achieve the final results stated elsewhere in this report.

A further problem encountered using coaxial components was related to the unreliability of their connectors. Several times during the course of the project, severe instability was found to be due to faulty or failed connectors, probably due in part to the inadequate method of support used. Further work would have to include recommendations for the rigid mounting of individual components. This has not been done up to the present because of the problems caused by frequent changes in the layout of the prototype and by the complication of insulating some components.

4.9 Leakage

When measuring attenuation values of up to 20 dB, the attenuation in the leakage path must be at least 100 dB to keep the measurement error below 0.001 dB. This has been achieved by wrapping copper tape around all joints and by sleeving leaky components, such as dc blocks, with steel wool in plastic bags.

4.10 Digital voltmeter errors

Errors introduced by the dvm are negligible compared with the errors due to noise on the output signal. They are therefore ignored.

to ± 0.0004 dB by taking multiple readings and applying statistical methods. The beating is quite a major problem and will be dealt with separately in section 4.7.

Electromagnetic interference is a problem at the very low levels used in the system. This is overcome partially by encasing the power heads in steel cases. The main problem area however is in the interconnections between the power heads and also between the heads and the power meter. The solution used is to run all the sensitive wiring through flexible steel conduit. Finally the power meter itself was encased in a mild steel box. These precautions were found to be necessary and adequate.

4.7 Beating at the output of the dc amplifier

Pulsing the microwave power at a pulse repetition frequency of 'f' Hz causes an undesirable residual ac component to be superimposed on the integrated dc output of the power head. If 'f'- or a harmonic of 'f'- is close to the chopper frequency of the power head (110 Hz), then beating occurs. In a manual system, slow beating is easily noticed because the needle on the power meter will oscillate (and corrective action can be taken at an early stage).

In the automated system, beating cannot be easily detected because of the digitisation of the dc signal. The effect of beating will not be evident until the measurement is completed, when the final result would show a large standard deviation, or an obvious error, for particular values of attenuation. In this case, the only corrective action available is to change the pulse width and prf and repeat the measurement at a different balance point. There would seem to be no other clear solution to this problem.

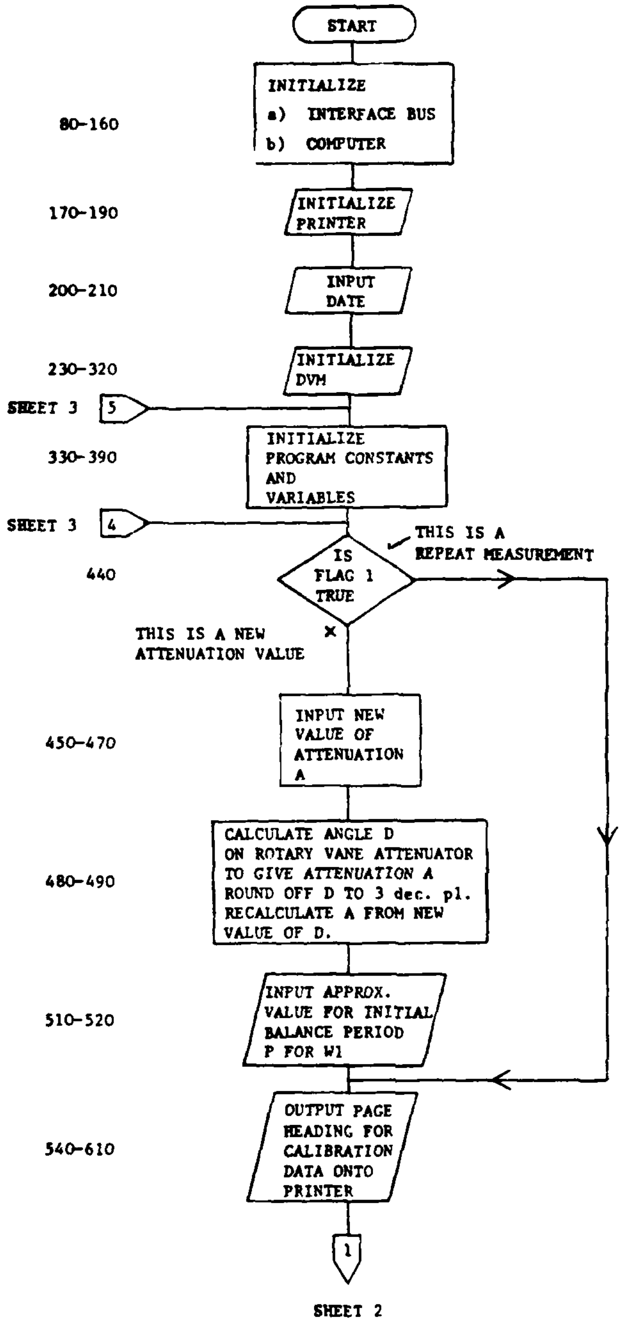
a) This problem has been mainly overcome by lagging the heads with polystyrene and cotton wool and we are now able to neglect the effect of ambient changes inside our temperature controlled laboratory.

b) When the time synthesizer parameters are changed, its output is switched off for 500ms. This holds the PIN switch in the off position and the mean power is temporarily drastically reduced which would cause a large imbalance in the power meter, driving it into saturation. The time needed for the amplifier to recover from being driven into saturation is of the order of 30 seconds, implying a settling time of 30 seconds after every change of period. This time is actually halved by inserting 70 dB of attenuation into the series attenuator during any change of the period. This switches the power off to both heads thus restricting the imbalance. An imbalance does still occur however due to the two heads having different thermal time constants, ie the residual heat in the heads causes a voltage to be generated which is of different duration and amplitude for each head. A settling time of 15 seconds is therefore necessary for thermal equilibrium to be restored once the new period has been set up. This is a major drawback to the system as a minimum calibration time for one attenuation point is about 12 minutes. This is at least 3 times longer than that for the other methods which are available.

Another source of error in this part of the system is due to instability at the output of the power meter caused by noise from the amplifier/TFT head combination and also by beating of the residual ac component on the signal from the power head and the chopper on the input of the power meter. The former is constant noise of about ± 0.001 dB on the output and can be reduced

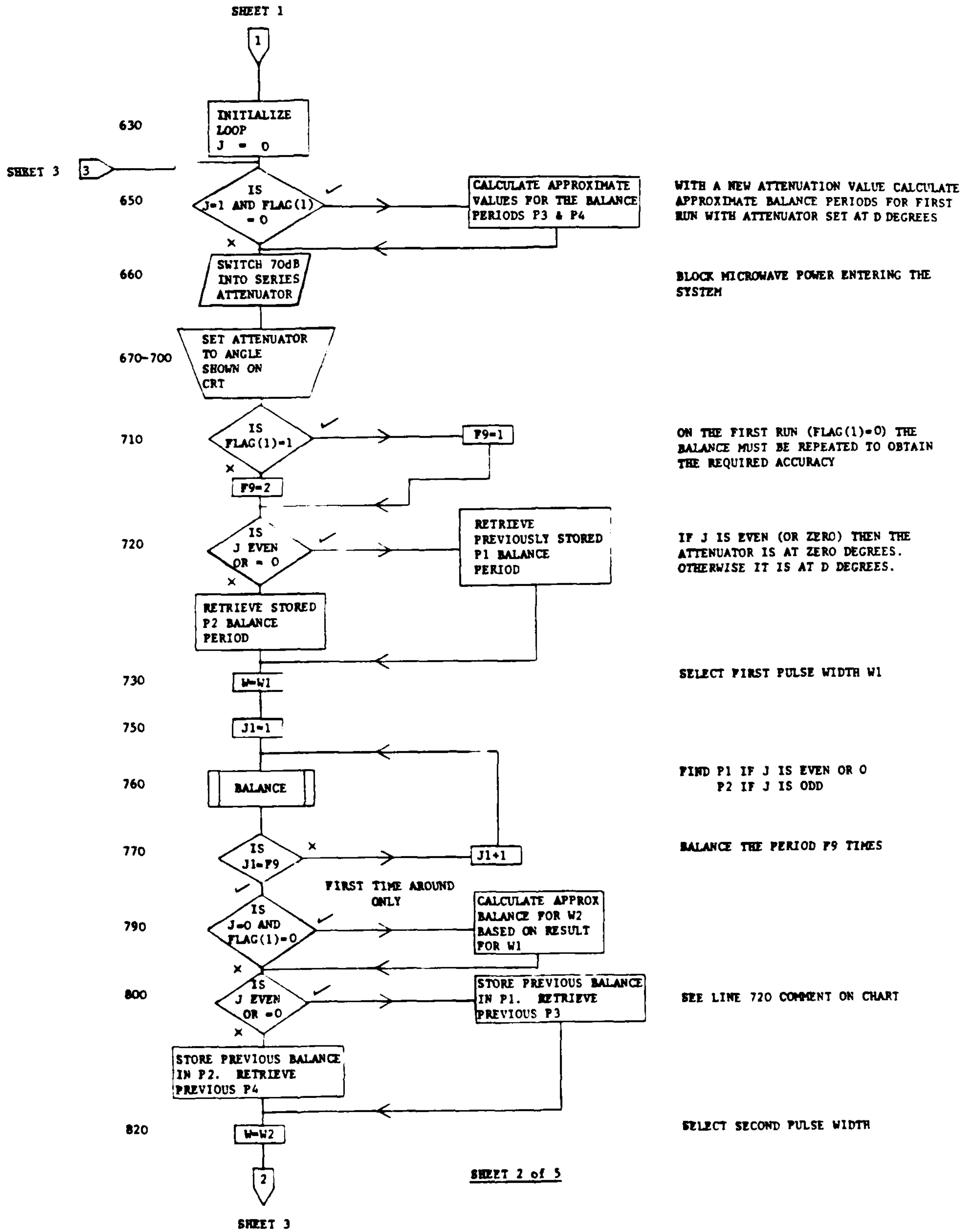
A.2.0 Appendix 2

This appendix consists of simplified flow diagrams for the two major sections of the program in appendix 3. The first chart is the main calibration program and the second is the subroutine used to automatically balance the system to obtain a series of period values for the least squares fit routine.

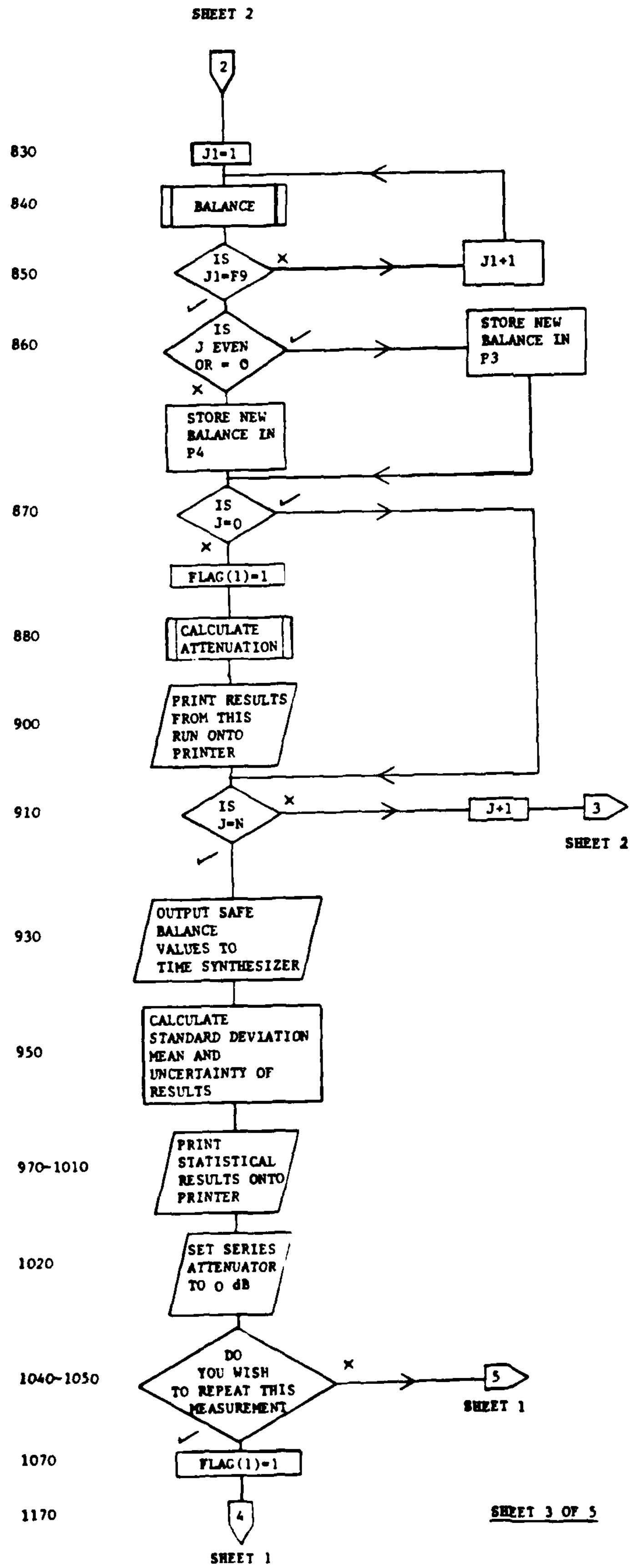


FIND THE VALUE OF ATTENUATION CLOSEST TO THAT REQUIRED WHICH CAN BE EASILY RESET ON THE ROTARY VANE ATTENUATOR.

BALANCE THE SYSTEM MANUALLY FOR AN APPROXIMATE VALUE FOR THE BALANCE PERIOD P ON THE FIRST PULSE WIDTH W1.


SHEET 1
1
630
INITIALIZE LOOP J = 0
SHEET 3
3
650
IS J=1 AND FLAG(1) = 0
CALCULATE APPROXIMATE VALUES FOR THE BALANCE PERIODS P3 & P4
WITH A NEW ATTENUATION VALUE CALCULATE APPROXIMATE BALANCE PERIODS FOR FIRST RUN WITH ATTENUATOR SET AT D DEGREES
660
SWITCH 70dB INTO SERIES ATTENUATOR
BLOCK MICROWAVE POWER ENTERING THE SYSTEM
670–700
SET ATTENUATOR TO ANGLE SHOWN ON CRT
710
IS FLAG(1)=1
F9=1
F9=2
ON THE FIRST RUN (FLAG(1)=0) THE BALANCE MUST BE REPEATED TO OBTAIN THE REQUIRED ACCURACY
720
IS J EVEN OR = 0
RETRIEVE PREVIOUSLY STORED P1 BALANCE PERIOD
IF J IS EVEN (OR ZERO) THEN THE ATTENUATOR IS AT ZERO DEGREES. OTHERWISE IT IS AT D DEGREES.
RETRIEVE STORED P2 BALANCE PERIOD
730
W=W1
SELECT FIRST PULSE WIDTH W1
750
J1=1
760
BALANCE
FIND P1 IF J IS EVEN OR 0
P2 IF J IS ODD
770
IS J1=F9
J1+1
BALANCE THE PERIOD F9 TIMES
FIRST TIME AROUND ONLY
790
IS J=0 AND FLAG(1)=0
CALCULATE APPROX BALANCE FOR W2 BASED ON RESULT FOR W1
800
IS J EVEN OR =0
STORE PREVIOUS BALANCE IN P1. RETRIEVE PREVIOUS P3
SEE LINE 720 COMMENT ON CHART
STORE PREVIOUS BALANCE IN P2. RETRIEVE PREVIOUS P4
820
W=W2
SELECT SECOND PULSE WIDTH
2
SHEET 3

SHEET 2 of 5



FIND P3 IF J IS EVEN OR EQUAL TO ZERO
P4 IF J IS ODD

IF J IS EVEN OR EQUAL TO ZERO THEN THE ATTENUATOR IS AT ZERO DEGREES. OTHERWISE IT IS SET TO D DEGREES.

THIS BYPASS IS USED ON THE FIRST TIME THROUGH THE LOOP AS THERE IS INSUFFICIENT INFORMATION TO CALCULATE ATTENUATION

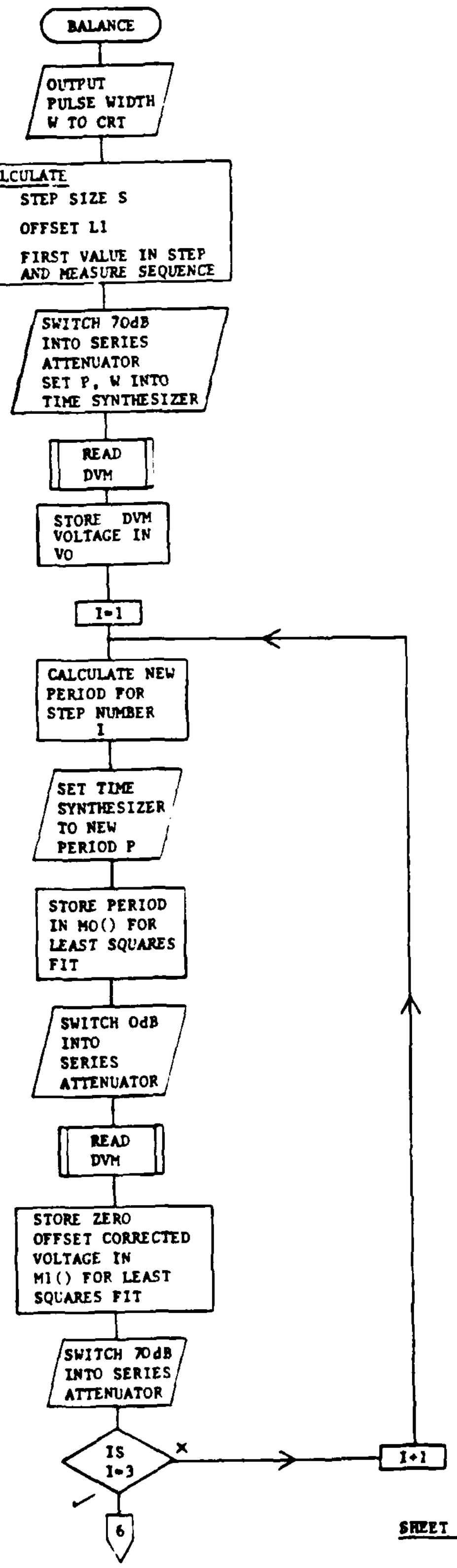
IF J IS NOT EQUAL TO THE NUMBER OF RUNS REQUIRED, JUMP BACK TO LINE 650

SET THE TIME SYNTHESIZER UP WITH A SET OF SAFE VALUES TO STOP ANY DAMAGE OCCURRING TO THE POWER HEADS

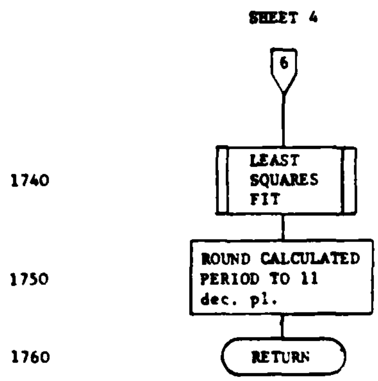
UNBLOCK THE MICROWAVE POWER. THE SYSTEM IS NOW ABLE TO MAINTAIN THERMAL EQUILIBRIUM OF THE POWER HEADS.

IF THIS MEASUREMENT IS TO BE REPEATED THEN SET FLAG(1) AND GOTO LINE 430 OTHERWISE GOTO LINE 340

BALANCE SUBROUTINE FLOW CHART



1510	
1530	DISPLAY CURRENT PULSE WIDTH
1540-1570	CALCULATE THE STEP AND MEASURE PARAMETERS
1580-1590	BLOCK MICROWAVE POWER INTO SYSTEM
1600	READ THE POWER METER OFFSET VOLTAGE
1610	
1620	INITIALIZE STEP COUNTER
1630	CALCULATE THE NEW PERIOD FOR EACH STEP
1640	
1650	STORE THE NEW PERIOD FOR PROCESSING LATER
1670	SWITCH MICROWAVE POWER INTO SYSTEM
1680	READ POWER METER OUTPUT VOLTAGE WITH POWER ON
1690	CORRECT VOLTAGE FOR ZERO OFFSET THEN STORE FOR PROCESSING LATER
1710	BLOCK MICROWAVE POWER INTO SYSTEM
1730	HAVE THREE STEPS BEEN CARRIED OUT, IF NOT INCREMENT STEP COUNTER AND REPEAT FOR ANOTHER MEASUREMENT


SHEET 4
6
1740
LEAST SQUARES FIT
1750
ROUND CALCULATED PERIOD TO 11 dec. pl.
1760
RETURN

A.3.0 Appendix 3

The following is a listing of the BASIC computer program used to calibrate a precision rotary vane attenuator using the Time Ratio Attenuator Calibrator.

```
10 ! PCCAL   1/11/84  14:23
20 ! TIME RATIO ATTENUATOR CALIBRATOR- ROTARY VANE ATTENUATOR VERSION
30 ! AUTOMATED BALANCE DETERMINATION BY LEAST SQUARES FIT
40 ! P.CUMMINGS
50 ! Crown Copyright Reserved 1984
60 !
70 ! Initialize system
80 RESET 7 ! Initialize interface bus
90 OPTION BASE 1
100 DEG
110 CLEAR
120 INTEGER F9,I,I1,J,J1,K,K1,N,N8,N9,S2
130 REAL A,D,L1,P,P1,P2,P3,P4,R1,R2,R3,S,T,V,V0,V1,V9,W,W1,W2,X1,X2,X3
140 DIM D$[18],V$[18],Y$[18],A$[5],B$[17]
150 DIM A(10,2),M(2),S(2),E(2),U(2)
160 DIM M1(3,2),M0(3),S0(2),I0(2),P0(2)
170 ! Set Epson MX80 printer to 132 characters wide
180 PRINTER IS 704,132
190 PRINT CHR$ (15)&CHR$ (27)&"Q"&CHR$ (132)
200 DISP "INPUT DATE"
210 INPUT D$
220 CLEAR
230 ! Initialise Solartron 7060 DVM
240 CLEAR 723 @ RESUME 7
250 WAIT 500
260 OUTPUT 723 ;"D3F0N1Q1R0T0"
270 TRIGGER 723
280 WAIT 2000
290 S2=SPOLL (723)
300 ENTER 723 ; V$
310 ON INTR 7 GOSUB 1910
320 SEND 7 ; UNT MTA UNL DATA ""
330 ! Initialise program variables
340 CFLAG 1 ! Clear remeasurement flag
350 N=6 ! Set number of measurements to be made
360 W1=.000015 @ W2=.000007 ! Set pulse widths
370 Y$=""
380 A$="  *  "
390 B$="ATTENUATION VALUE"
400 !
410 ! Start of measurement program
420 !
430 CLEAR
440 IF FLAG (1) THEN GOTO 550 ! If this is a repeat measurement then jump forwar
d
450 ! Input new value to be measured
460 DISP "INPUT ";B$
470 INPUT A
480 D=INT (ACS (1/10^(A/40))*1000)/1000 ! Calc angle and round to 3 dec. pl.
490 A=40*LGT (1/COS (D)) ! Recalculate atten based on angle D being used
500 ! Input initial balance value on first run
510 DISP "INPUT INITIAL PERIOD IN mS"
520 INPUT P
530 P1=P/1000 ! Convert P to seconds
540 ! Output heading to printer
550 PRINT USING "#,3/,K,K,/,K" ; "DATE= ",D$,"POWER LEVEL AT INPUT= 25mW"
560 PRINT "REF ATTEN = 10dB"
570 PRINT "PIN DIODE No. 002"
580 PRINT @ PRINT
```

```
'0 PRINT USING "#,K,X,DDZ.4D,3A,/,K,X,DDZ.4D,4A,2/" ; B$,A," dB","ANGLE=",D," d
;"
)0 PRINT USING 1470 ; "PULSE WIDTHS","W1 = ",W1*1000000," uS","W2 = ",W2*100000
," uS"
.0 PRINT USING 1480 ; "P1(mS)","P2(mS)","A1-W1(dB)","P3(mS)","P4(mS)","A2-W2(dB
'
:0 ! Measurement loop
:0 FOR J=0 TO N
)0 ! Calc approx values for balance at atten setting on first atten balance run

50 IF NOT FLAG (1) AND J=1 THEN P2=(10^(-(A/10)))*P1 @ P4=(10^(-(A/10)))*P3
60 OUTPUT 726 ;"A5678" ! Block power during attenuator movement
70 DISP "SET ATTEN TO ";
30 IF J MOD 2=0 THEN DISP "ZERO" ELSE DISP USING "DZ.3D,K" ; D," deg"
90 BEEP 350,25 @ BEEP 280,25 @ BEEP 235,30 @ BEEP 280,30 @ BEEP 350,30 @ BEEP 1
0,100
00 PAUSE
10 IF FLAG (1) THEN F9=1 ELSE F9=2 ! On J=0 and J=1, balance twice at each valu
 for greater accuracy
20 IF J MOD 2=0 THEN P=P1 ELSE P=P2 ! Select previous balance period this balan
e.J even is zero degrees
30 W=W1 ! Select first pulse width
40 ! Balance once or twice depending on whether this is first measurement at th
s value
50 FOR J1=1 TO F9
60 GOSUB 1520 ! Gosub the BALANCE subroutine
70 NEXT J1
80 ! Calculate approx value for balance with pulse width W2 (empirical correcti
n factor)
90 IF NOT FLAG (1) AND J=0 THEN P3=P*(W2*.9996504)/W1
00 IF J MOD 2=0 THEN P1=P @ P=P3 ELSE P2=P @ P=P4 ! Store the W1 balance and ge
 old W2 balance
10 ! Load the second pulse width and repeat the procedure above
20 W=W2 ! Load the second pulse width
30 FOR J1=1 TO F9
40 GOSUB 1520 ! Gosub the BALANCE subroutine
50 NEXT J1
60 IF J MOD 2=0 THEN P3=P ELSE P4=P ! Store the new balance point for W2
70 IF J=0 THEN GOTO 910 ELSE SFLAG 1 ! On the first time round jump past the at
en calculation
80 GOSUB 1270 ! Gosub the ATTENUATION CALCULATION subroutine
90 ! Print the results of the last run and calculation
00 PRINT USING 1490 ; P1*1000,A$,P2*1000,A$,A(J,1),A$,P3*1000,A$,P4*1000,A$,A(J
2)
10 NEXT J
20 ! Terminate measurement
30 OUTPUT 724 ;"P";P1;",W";W1 ! Output safe values to time synthesizer
40 LOCAL 7 @ REMOTE 7 ! Release instruments on bus to local control
50 GOSUB 1320 ! Gosub STATISTICS subroutine
60 ! Output statistical results to printer for both pulse widths
70 FOR J=1 TO 2
80 PRINT @ PRINT "PULSE WIDTH= ";
90 IF J=1 THEN PRINT USING "DDZ.D,K" ; W1*1000000," uS" ELSE PRINT USING "DDZ.D
K" ; W2*1000000," uS"
000 PRINT USING "#,K,DZ.5D,/" ; "MEAN= ",M(J),"SD= ",S(J),"ERROR= ",E(J),"UNCER
= ",U(J)
010 NEXT J
020 OUTPUT 726 ;"B5678" ! Switch on power to maintain power head temperature
030 PRINT CHR$ (12) ! Take a new page
040 CLEAR @ DISP "DO YOU WISH TO REPEAT PREVIOUS","MEASUREMENT? Y/N"
```

```
1050 INPUT Y$@ IF Y$="Y" THEN GOTO 1070
1060 IF Y$="N" THEN GOTO 340 ELSE GOTO 1040
1070 SFLAG 1 ! Set remeasurement flag, allows faster measurement second time aro
und
1080 ! Disp balance periods on screen for possible modification
1090 CLEAR @ DISP USING "K,2/" : P1,P2,P3,P4
1100 DISP "DO YOU WISH TO CHANGE ANY","PERIODS? Y/N"
1110 INPUT Y$@ IF Y$="N" THEN GOTO 430
1120 IF Y$#"Y" THEN GOTO 1090
1130 DISP "INPUT P1" @ INPUT P1
1140 DISP "INPUT P2" @ INPUT P2
1150 DISP "INPUT P3" @ INPUT P3
1160 DISP "INPUT P4" @ INPUT P4
1170 GOTO 430 ! Repeat measurement
1180 !
1190 ! CHANGE PERIOD subroutine
1200 OUTPUT 726 ;"A5678" ! Block microwave power to system
1210 OUTPUT 724 ;"P",P ! Change period of synthesizer output
1220 WAIT 700 ! Allow synthesizer to set up new parameters
1230 OUTPUT 726 ;"B5678" ! Unblock microwave power
1240 LOCAL 7 @ REMOTE 7 ! Free bus instruments to local control
1250 RETURN
1260 !
1270 ! ATTENUATION CALCULATION subroutine
1280 A(J,1)=10*LGT (P1/P2) ! Calculate attenuation for W=W1
1290 A(J,2)=10*LGT (P3/P4) ! W=W2
1300 RETURN
1310 !
1320 ! STATISTICS subroutine
1330 T=2.57058 ! STUDENT'S t factor for N=6
1340 FOR K=1 TO 2 ! Evaluate statistical results for attenuation results, K=1 is
 W1, K=2 is W2
1350 X1=0
1360 X2=0
1370 FOR J=1 TO N
1380 IF J=1 THEN X3=A(1,K) ELSE X1=X1+A(J,K)-X3 ! Code data around first value
1390 X2=X2+(A(J,K)-X3)*(A(J,K)-X3)
1400 NEXT J
1410 S(K)=SQR ((X2-X1*X1/N)/(N-1)) ! Evaluate standard deviation
1420 M(K)=X3+X1/N ! Evaluate mean
1430 E(K)=M(K)-A ! Calculate Rotary Vane Atten deviation from theoretical law
1440 U(K)=SQR (S(K)*S(K)*T*T/N) ! Calculate random uncertainty for 95% confidenc
e
1450 NEXT K
1460 RETURN
1470 IMAGE #,K,/,K,3D.D,K,/,K,3D.D,K,2/
1480 IMAGE 2X,K,9X,K,6X,K,6X,K,9X,K,6X,K
1490 IMAGE DZ.7D,K,DZ.7D,K,DZ.4D,K,DZ.7D,K,DZ.7D,K,DZ.4D
1500 !
1510 '   BALANCING subroutine
1520 CLEAR
1530 DISP @ DISP @ DISP "BALANCING AT ";W*1000000;" uS"
1540 R3=P ! Copy initial period
1550 S=INT (R3*.0003*100000000000)/100000000000 ! Calculate step size
1560 L1=INT (3*S*100000000000/2)/100000000000
1570 R1=R3-L1 ! Calculate first value in step and measure sequence
1580 OUTPUT 726 ;"A5678" ! Block microwave power
1590 OUTPUT 724 ;"W",W,",P",P ! Output new values to time synth.
1600 GOSUB 1790 ! Call READ DVM subroutine
1610 V0=V9 ! Store zero power input offset voltage
```

```
FOR I=1 TO 3 ! Step and measure sequence
R2=R1+(I-1)*S ! Calculate period
OUTPUT 724 ;"P",R2 ! Output period to time synth.
M0(I)=R2 ! Store period for least squares fit
WAIT 600
OUTPUT 726 ;"B5678" ! Unblock microwave power
GOSUB 1790 ! Call READ DVM
M1(I,1)=V9-V0 ! Correct voltage for zero offset and store for least squares

M1(I,2)=1 ! Straight line coefficient of zero crossing point is always 1
OUTPUT 726 ;"A5678" ! Block microwave power into system
WAIT 600
NEXT I
GOSUB 1990 ! Call LEAST SQUARES FIT subroutine
P=INT (S0(2)*100000000000)/100000000000 ! Round calculated balance period t
dec. pl.
RETURN
!
! READ DVM subroutine
ENABLE INTR 7;8 ! Enable DVM service request to interrupt computer
N8=10 @ V9=0 ! Do ten measurements and take the mean
WAIT 10000
FOR N9=1 TO N8
TRIGGER 723 ! Trigger DVM to take one measurement
CFLAG 2 ! Clear "DVM has been read" flag
WAIT 1 ! Wait 1ms
IF NOT FLAG (2) THEN GOTO 1850 ! If DVM has not finished reading then wait
ier 1ms.
V9=V9+V ! Accumulate the 10 DVM readings
NEXT N9
V9=V9/N8 ! Take the mean of the 10 readings
RETURN
STATUS 7,1 ; S2 ! Dummy check of interrupt cause to clear status register i
3S
IF NOT BINAND (SPOLL (723),16) THEN 1960 ! Return to main program if readin
t complete
ENTER 723 ; V$ ! Read DVM
V=VAL (V$)
SFLAG 2 ! Set "DVM has been read" flag
ENABLE INTR 7;8 @ RETURN ! Re-enable interrupt and return to main program
!
!
!   REAL LEAST-SQUARES FITTING PROCEDURE
!   THE MATRIX (ARRAY) M1 HAS N0 ROWS (ONE FOR EACH EQUATION) AND N1
!   COLUMNS (ONE FOR EACH UNKNOWN).  THE RIGHT-SIDES ARE STORED IN
!   THE ARRAY M0, WHICH HAS N0 ELEMENTS.  M1 AND M0 ARE OVERWRITTEN
!   DURING THE SOLVING PROCESS.  THE SOLUTION IS RETURNED IN S0,
!   WHICH HAS N1 ELEMENTS.  THIS PROCEDURE IS ADAPTED FROM AN NPL
!   IMPLEMENTATION OF THE METHOD OF HOUSEHOLDER, DESCRIBED BY
!   PETERS & WILKINSON (COMP. J. 1970, P. 309).
!   IT DELIVERS THE MINIMUM-NORM LEAST-SQUARES SOLUTION.
!
INTEGER L
REAL F,G,H,R,Q,S1
R=0
FOR J1=1 TO N1
S1=0
FOR I1=1 TO N0
S1=S1+M1(I1,J1)^2
NEXT I1
```

```
2170 IF R>= S1 THEN 2200
2180 R=S1
2190 L=J1
2200 NEXT J1
2210 FOR K1=1 TO N1
2220 I0(K1)=L
2230 IF L=K1 THEN 2290
2240 FOR I1=1 TO N0
2250 Q=M1(I1,L)
2260 M1(I1,L)=M1(I1,K1)
2270 M1(I1,K1)=Q
2280 NEXT I1
2290 F=M1(K1,K1)
2300 G=SQR (R)
2310 IF F>= 0 THEN G=-G
2320 M1(K1,K1)=G
2330 H=R-F*G
2340 F=F-G
2350 P0(K1)=F
2360 R=0
2370 FOR J1=K1+1 TO N1
2380 G=F*M1(K1,J1)
2390 FOR I1=K1+1 TO N0
2400 G=G+M1(I1,K1)*M1(I1,J1)
2410 NEXT I1
2420 G=G/H
2430 M1(K1,J1)=M1(K1,J1)-F*G
2440 S1=0
2450 FOR I1=K1+1 TO N0
2460 M1(I1,J1)=M1(I1,J1)-G*M1(I1,K1)
2470 S1=S1+M1(I1,J1)^2
2480 NEXT I1
2490 IF R>= S1 THEN 2520
2500 R=S1
2510 L=J1
2520 NEXT J1
2530 NEXT K1
2540 FOR K1=1 TO N1
2550 F=P0(K1)
2560 H=F*M1(K1,K1)
2570 G=F*M0(K1)
2580 FOR I1=K1+1 TO N0
2590 G=G+M1(I1,K1)*M0(I1)
2600 NEXT I1
2610 G=G/H
2620 M0(K1)=M0(K1)+F*G
2630 IF K1=N1 THEN 2670
2640 FOR I1=K1+1 TO N0
2650 M0(I1)=M0(I1)+G*M1(I1,K1)
2660 NEXT I1
2670 NEXT K1
2680 FOR I1=N1 TO 1 STEP -1
2690 F=M0(I1)
2700 FOR K1=I1+1 TO N1
2710 F=F-M1(I1,K1)*S0(K1)
2720 NEXT K1
2730 S0(I1)=F/M1(I1,I1)
2740 NEXT I1
2750 FOR I1=N1-1 TO 1 STEP -1
2760 L=I0(I1)
```

```
F L=I1 THEN 2810
=S0(L)
0(L)=S0(I1)
0(I1)=F
EXT I1
ETURN
ND
```

Table 1 MEASUREMENT RESULTS

Device Under Test	Rotary Vane Attenuator				Switched Coupler	
Nominal Attenuation, dB	5	10	15	20	10	20
Measured attenuation, dB (a) and random uncertainty for 95% confidence (dB x 10^{-5})	5.00038	9.99982	14.99968	19.99660	10.64461	20.38133
	(24)	(32)	(40)	(66)	(32)	(35)
	5.00093	9.99990	14.99953	19.99715	10.64479	20.38129
	(22)	(37)	(24)	(38)	(23)	(43)
	5.00092	9.99979	14.99972	19.99785	10.64482	20.38140
	(19)	(25)	(26)	(41)	(45)	(37)
	5.00102	9.99991	14.99946	19.99780	10.64458	20.38119
	(20)	(20)	(40)	(57)	(56)	(33)
Calibration, dB (b) and random uncertainty for 95% confidence (dB x 10^{-5})	5.0006 (33)	9.9997 (22)	14.9999 (37)	19.9953 (45)	10.6448 (17)	20.3795 (21)
Mean Difference, dB	0.0002	-0.0001	-0.0003	0.0021	-0.0001	0.0018

(a) Time Interval Ratio Measurement

(b) UK National Standard Measurement

Table 2

PIN diode supply voltage test 1

Negative supply kept at -6.37V ± 10mV

Positive supply volts	Nominal Attenuation 10 dB	20 dB
1.08	10.001	19.999
1.13	10.001	20.000
1.16	10.000	19.998
1.38	10.000	19.999
1.66	10.000	19.998
2.18	10.001	20.000
2.62	10.000	19.998
3.29	10.001	20.000

Table 3

PIN diode supply voltage test 2

Positive supply kept at +1.69V ± 10mV

negative supply volts	Nominal Attenuation 10 dB	20 dB
6.37	10.000	19.998
5.99	10.000	19.998
5.02	10.000	19.999
4.02	9.999	19.998
3.00	9.997	19.996
1.97	9.993	19.990

Table 4

PIN diode incident power changes

Nominal attenuation (dB)	Error in result dB and (95% uncertainty x 10^-4)
0-5 dB	0.0004 (6)
	0.0007 (10)
	0.0009 (5)
	0.0002 (2)
5-10 dB	0.0002 (8)
	0.0008 (10)
0-10 dB	0.0001 (4)
	0.0011 (7)
	0.0009 (4)

Table 5

Mark/space stability test

Pulse width (μS)	Error in dB referred to 15 μS pulse width		
	DUT=0 dB	DUT=100 dB	DUT=20 dB
1	-0.0089	-0.0095	-0.0124
2	-0.0026	-0.0039	-0.0021
3	0.0003	-0.0016	-0.0032
4	0.0005	0.0000	-0.0017
5	0.0005	0.0000	-0.0018
6	0.0010	0.0000	-0.0013
7	0.0008	0.0000	0.0000
8	0.0007	0.0000	0.0000
9	0.0005	0.0000	0.0000
10	0.0005	0.0000	0.0000
15	0.0000	0.0000	0.0000

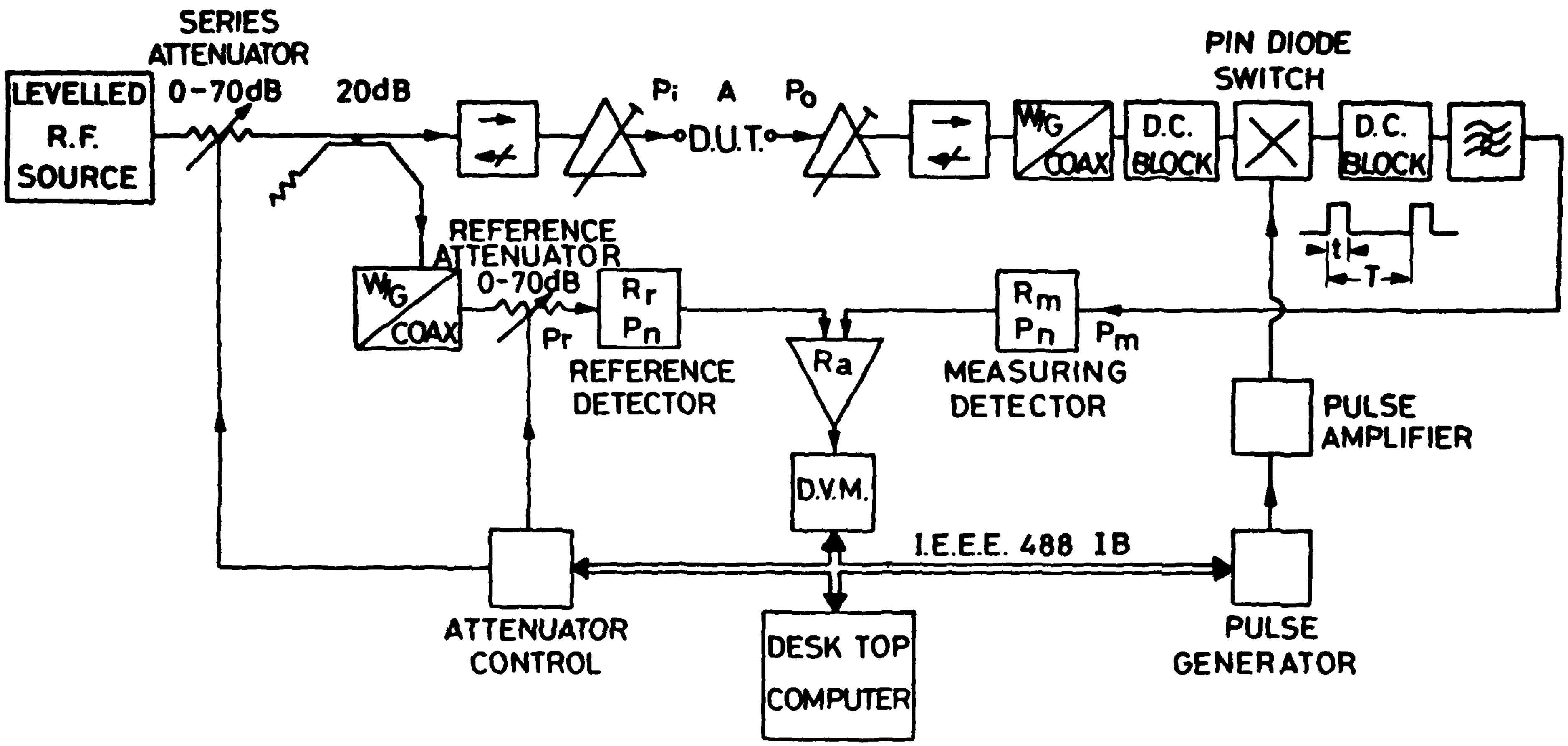
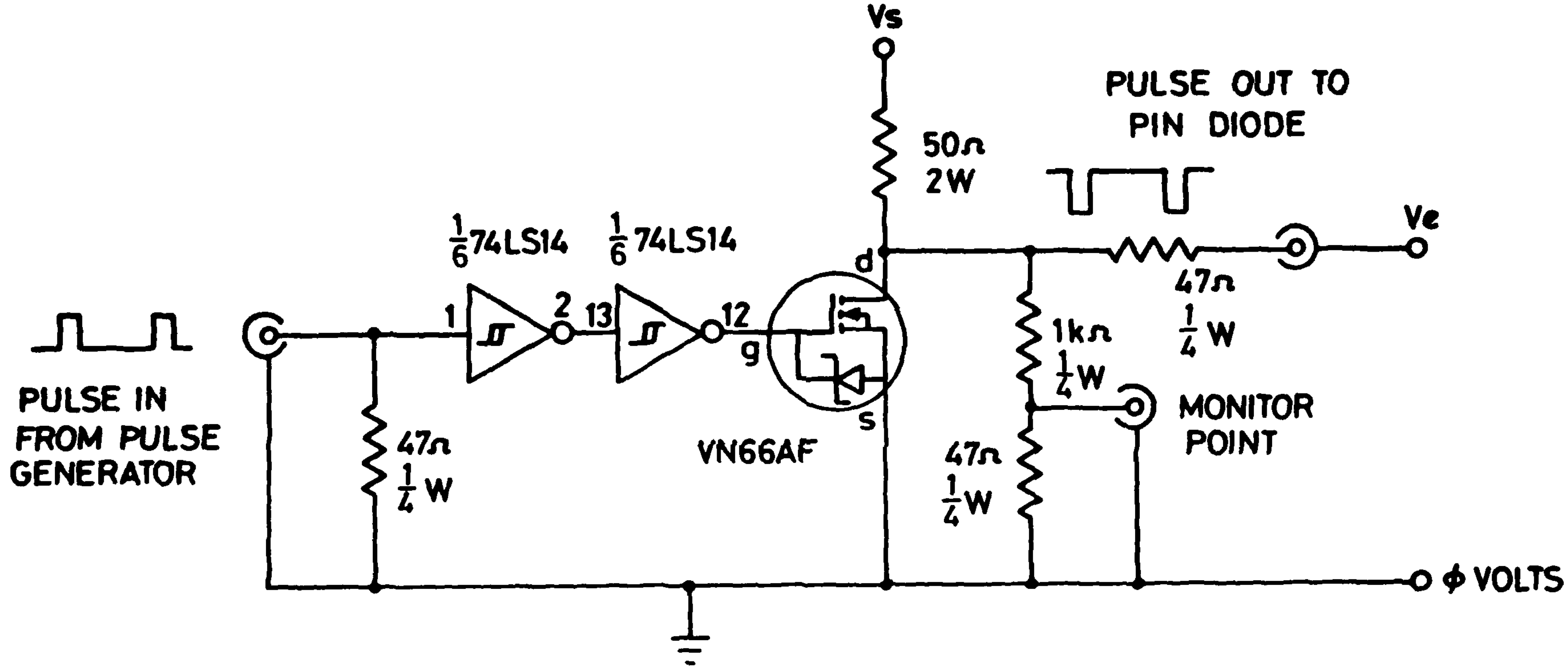


Figure 1: Attenuation Measurement by Time Interval Ratio.



Vs AND Ve ARE DERIVED FROM VOLTAGE REGULATORS IMMEDIATELY ADJACENT TO THE CIRCUIT ITSELF. ALL RESISTORS ARE CARBON TO MINIMISE INDUCTANCE

Figure 2: PIN Diode Driver Circuit.

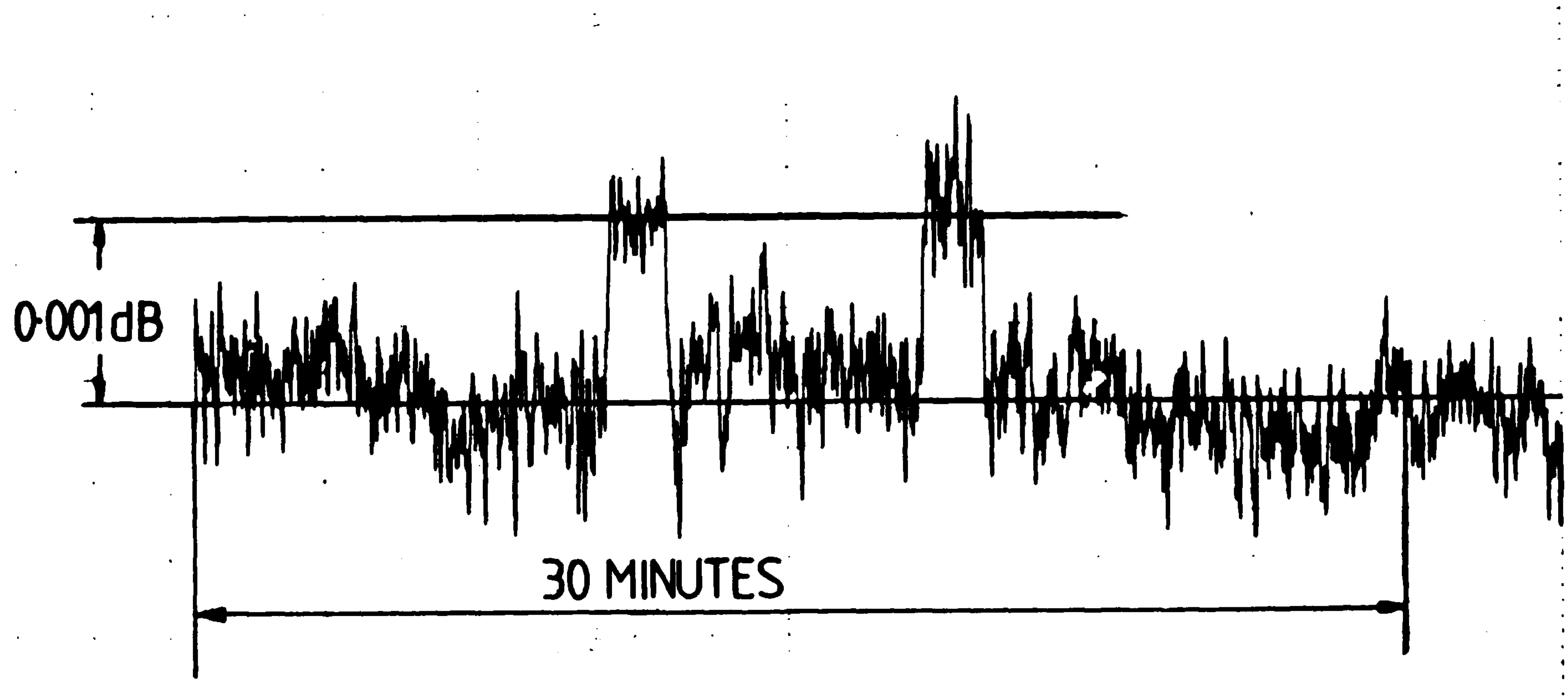


Figure 3: System Stability and Resolution.

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7. Title

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7a. Title in Foreign Language (in the case of translations)

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Abstract

A method of measuring microwave attenuation by substitution is described. As attenuation is inserted into the device under test, the pulse repetition frequency of a pulse modulated PIN diode switch in series with the device is changed to maintain a constant mean power output from the circuit. The ratio of the pulse repetition frequencies before and after insertion is shown to be simply related to the attenuation of the device under test.

Sources of error are examined in detail and results are quoted showing inaccuracies of less than $\pm$ 0.002 dB over a range of 0 to 20 dB.

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